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DEVELOPMENTS AND APPLICATIONS OF THE NUMERICAL ANALYSIS OF TUNNELS IN CONTINUOUS MEDIA

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1. INTRODUCTION

Tunneling engineering is perhaps one of the areas of applied soil and rock mechanics in which the numerical methods for stress analysis (i.e. those based on the discretization of continua and on algorithms requiring the use of programmable computers) are more frequently adopted in practice.[1]

Their frequent use depends on several reasons related to the complex characteristics of the tunneling problems. One of the most important is the strong influence of the excavation and construction procedures, and of their technological details, on the stress/strain distribution in the rock surrounding the opening and in its support system. This represents a main drawback for the analytical solutions, or for the approximated 'standard' methods of analysis, which in most cases cannot consider this process with sufficient approximation. On the contrary, the excavation/construction steps can be simulated in a numerical analysis with a degree of accuracy which in principle is limited only by the required computational effort.

Another important aspect of tunneling problems that can be accounted for in a numerical analysis is their complex geometrical nature. This is not only related to the shape of the opening, but also to the presence of discontinuities in the rock mass, of non-homogenous or non-isotropic layers, etc. Also, the extension to 3D problems is straightforward, the main limit being again the required computer time.

Finally, these methods are able to solve problems, frequently met in tunneling engineering, characterized by a non-homogeneous initial stress distribution and by non-linear, time-dependent or multi-phase behaviour.

Here, a short overview is presented of the developments and applications of the numerical methods in tunneling engineering with particular reference to the problems involving continuous media. The case of discontinuous or fractured rock masses is discussed in a companion paper.

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No attempt is made to present a complete survey of such a vast and articulated topic. The mere aim of this brief note is to recall the areas in which the research effort was concentrated and to mention some of the relevant steps made in this field during the past years.

To reduce the extent of the discussion, the attention is focused mainly on the contributions related to tunneling problems, with minor emphasis on mining engineering and on the excavation of large underground chambers.

Among the various numerical techniques, the finite element method is considered with greater attention, without disregarding, however, other numerical approaches used in engineering practice.

2. DEVELOPMENTS AND APPLICATIONS

Since its early applications,[1] the finite element method appeared to be particularly suited for the solution of geotechnical engineering problems and for the stress analysis of tunnels and underground openings.[2–4] In fact, this method and other numerical techniques rapidly became practical tools which helped the designer in dimensioning the opening, in determining the loads carried by its support structures[5–8] and for quantitatively assessing its overall behaviour through parametric or sensitivity studies.[9]

As a consequence, the interest of the academic and professional communities for the use of numerical methods in tunneling engineering grown steadily during the years. An aspect of this trend is shown, for instance, by the choice of topics related to tunneling for some of the invited lectures at the conferences of the International Association for Computer Methods and Advances in Geomechanics.[10–13]

It should be observed, however, that the research did not concern solely the numerical techniques. In fact a non-negligible effort was also devoted to the formulation of new analytical or semi-analytical solutions, even though their range of applicability is usually narrower than that of numerical approaches.

These solutions refer to a variety of problems such as the evaluation of the pressure exerted by an elastic rock mass on tunnel support structures;[14,15] the determination of the elasto-plastic stress–strain regime around a cavity in media having a time-dependent behaviour,[16,17] or characterized by an initially non-hydrostatic stress field;[18] the effects induced by the driving process of a tunnel into a visco-elastic rock mass;[19] etc.

2.1. Simulation of tunneling processes in continuous and jointed masses

It was previously observed that a main advantage of the numerical solution methods consists in their ability to simulate excavation and construction processes. With this respect, it is important to observe that a correct numerical analysis of a tunnel requires the simulation of the excavation process through a procedure 'consistent' with the characteristics of the problem at hand.

For instance, when applied to a linearly elastic medium, a correct finite element simulation of an unsupported excavation should lead to final stress and strain fields which do not depend on the sequence of steps adopted in the calculations. On the contrary, a strong dependency of the stress–strain distribution on the excavation sequence may exist when dealing with supported openings or with non-linear material behaviour.

The theoretical bases and the practical implications of this type of simulation were treated in various papers, that considered both continuous elastic or elasto-plastic masses[20–22] and jointed rocks.[23]

With this respect, it can be observed that the presence of joints should not be neglected in the analysis of tunnels. The early simulations of jointed rock masses, based on the explicit modelling of each joint set,[24] did not show a large potential for practical application, due to the consequent complexity of the discretization. Further studies led to models which represent the discontinuous jointed rock mass as a non-isotropic, non-linear continuum. Among them the so-called 'multilaminate' model[25] and more recent models based on 'damage mechanics'[26,27] should be mentioned.

2.2. 2D vs 3D analyses

Having defined a correct procedure for simulating the removal of part of a pre-stressed medium, the numerical solution technique can be employed in the analysis of problems the geometry of which is continuously modified during excavation.

The advancing process of a tunnel, which has an essentially 3D nature, has been studied by various authors who introduced different hypotheses in order to reduce it to a simpler (and cheaper) 2D scheme. For instance, 2D axisymmetric finite element analyses were used in Reference 28 for simulating the advancing process of a tunnel in a visco-elastic rock mass; the use of Fourier series is suggested in Reference 29 for 'expanding' 2D solutions into the 3D regime, while the 2D plane strain approximation of the driving process is discussed in References 30 and 31. Nowadays, 2D models based on the so-called 'stiffness reduction method'[32] and 'stress reduction method'[33] are frequently adopted in the design of tunnels.

The computer programs able to carry out accurate numerical analyses of the excavation process were used for studying the influence of the construction procedure on the overall behaviour of tunnels, and on the stress distribution in their supports and in the surrounding rock.[34–37]

Specific excavation technologies were also analysed, like those involving the use of shotcrete,[38,39] of compressed air,[40] of mechanical shields,[41] of soil freezing,[42] of preliminary grouting of cohesionless soils[43] and of 'multiple' supports.[44]

Another advantage of the numerical approaches for stress analysis is their ability to solve problem having a complex geometry. This characteristics has been initially exploited for studying the interaction between parallel tunnels through 2D analyses.[45,46] Subsequently, the increasing power of programmable computers made it possible to solve actual 3D tunneling problems.[47,48]

Some of these studies concerned the stability of the tunnel in the vicinity of its face,[49,50] considering also the stabilizing effect of a slurry under pressure.[51,52] Other studies dealt with the stress–strain distribution in the vicinity of tunnel intersections,[53–55] or crossings,[56] taking also into account the non-linear and time-dependent behaviour of the rock.[57]

2.3. Surface settlements induced by tunneling

Quite naturally these studies developed towards the evaluation of the surface settlements caused by shallow excavations.[58,59] This problem was approached by various authors through relatively cheap, but still meaningful, 2D analyses.[60–64] These studies show that, once the parameters of the numerical model have been properly calibrated, this analysis scheme can lead to an acceptable agreement with the *in situ* measurements in spite of its apparent limitations.

It is recognized, however, that a more accurate evaluation of the surface settlements can be reached by 3D analyses. They permit, in fact, to account for the non-uniform stress distribution

along the length of the tunnel and for the effect of the deformation of the excavation face, which is particularly important for wide openings. To this purpose both the finite element method[65,66] and the boundary integral equation method[67,68] have been used in the literature.

The research on this topic is nowadays proceeding towards engineering problems of increasing complexity like, for instance, those related to the evaluation of the effects of the settlements induced by tunneling on the stability of existing buildings and masonry structure.[69]

2.4. 'Loss' of shear strength induced by tunneling

The difficulties encountered in driving and stabilizing a tunnel often depend on particular aspects of the constitutive behaviour of the rock among which the so-called 'strain softening' (i.e. the loss of shear strength with increasing shear deformation) plays a major role.

The early studies on this problem, that considered in particular the post failure behaviour of the rock mass,[70] were followed by publications based on more complex material models, which account for both pre- and post-peak behaviour. In particular, new analytical solutions for geometrically simple cases were presented,[71,72] as well as finite element studies based on various elasto-plastic constitutive laws[73–75] and, in particular, on Hoek–Brown criterion.[76,77]

Other contributions relevant to this topic dealt with the spreading of zones within which the 'damage' of rock takes place with various levels of intensity[78,79] and that can appreciably influence the stability of the opening.

2.5. Time-dependent and two-phase behaviour

Another important mechanical characteristic of rocks that cannot be neglected in tunneling is their time-dependent behaviour,[80–82] i.e. the tendency to deform increasingly during time under a constant stress state.

In some cases this phenomenon is strictly related to the properties of the natural rock, like in the case of rock salt.[83,84] In other instances, however, it can be induced by grouting[85] or by artificial freezing.[86]

In tunneling practice the time-dependent behaviour of natural rocks is customarily subdivided into two main categories, that are referred to as 'squeezing' and 'swelling' rocks.[87]

In a squeezing rock[88,89] the time-dependent deformation of the tunnel is produced by the increase of shear strains caused by the concentration of stresses in the vicinity of the excavation. In the case of swelling,[90] the stress variation and the increase in water content produce an increment of volume during time, which is frequently associated also to an increase in shear strains. Note that while squeezing (or creep) could be studied even considering the rock as a one phase (solid) material, the analysis of swelling should take into account the two phase nature of the medium.

A variety of numerical models has been proposed in the literature to study these effects and their influence on the pressure exerted by the rock on the liner. The numerical models used for squeezing range from those based on the so-called convergence-confinement method,[91] to 2D[92] and 3D[93] finite element models. Also, the swelling phenomenon has been introduced in the framework of the finite element method considering, as previously mentioned, the two-phase nature of the rock.[94–96]

Also other time-dependent aspects related to tunneling have been studied through numerical procedures. They depend, for instance, on the viscosity of the shotcrete used as a temporary support;[97] on the viscous deformation of soft clays, the behaviour of which was described through modified Cam-clay model;[98] on the possible loss of stiffness[99] and of shear resistance[100,101] of the rock during time, leading to delayed failure of the opening; on the so-called volumetric softening that models the destructuralization of natural clays subjected to an increase of stresses.[102,103]

Another important time-dependent effect is the one related to the consolidation of saturated clays. The pore pressure build up and/or dissipation induced by the driving process of a tunnel[104] represents one of the important phenomena that can be studied through suitably formulated numerical approaches.

Some of these studies considered in detail the hydrodynamics nature of the problem and deal, in particular, with the influence of the seepage flow towards the tunnel,[105,106] and of the lowering of the water table,[107] on the stability of the opening and on the loads carried by its liner. Other studies of similar nature are specifically related to the effects of tunneling on the groundwater regime in the surrounding medium.[108–110]

Various authors presented contributions on the analysis of the 'coupled' problems of water seepage induced by tunneling and of deformation of the soil skeleton. The numerical simulation of excavation processes in saturated poro-elastic media, accounting for the lowering of the water table, was discussed in Reference 111, while in Reference 112, the problem was studied accounting for the elasto-plastic behaviour of the soil, based on modified Cam-clay model, reaching the conclusion that squeezing can be adequately estimated by considering the dissipation of pore pressure induced by the excavation.

A series of studies concerned tunnels driven in saturated soils the time-dependent deformation of which is caused both by the dissipation of pore pressure and by the intrinsic viscous properties of the skeleton.[113–118] A variety of different constitutive laws were adopted in these analyses. They range from visco-elastic models,[114] that allow for the formulation of semi analytical solutions, to Cam-clay model,[116] to models that attempt to introduce the effects of the so called primary, secondary and tertiary creep stages.[118]

2.6. Dynamics problems

Eventhough in engineering practice tunnels are often designed considering only static or quasi static (e.g. creep) loading conditions, a non-negligible research effort has been devoted to investigating their behaviour in dynamic conditions.

Some of these studies concerned the effects of the vibrations produced by trains on the tunnel itself or on adjacent structures,[119,120] while other applications considered the dynamic excitation produced on tunnels by blast loading at the ground surface[121] or below the surface.[122–124]

In References 125 and 126, the effects of joints on the propagation of waves within discontinuous rock masses has been considered, as well as the possible induced loosening of the rock facing the tunnel.

In addition to the effects of blasting also those due to earthquakes have been studied.[127] These researches considered tunnels and underground openings in various conditions[128–131] and had a relatively broad spectrum. They range, in fact, from the attempt to set-up criteria for the design of underground structures subjected to earthquakes[132] to typical problems of engineering seismology, dealing with the influence of underground openings on the propagation of the seismic waves.[133,134]

2.7. Boundary integral equation method and 'coupled' approaches

It was previously observed that, eventhough the finite element method is still the most popular numerical technique in engineering practice, other alternative methods are frequently used in applied soil and rock mechanics. Among them the boundary integral equation method, or boundary element method, is perhaps the most significant.[135–137]

This method, in fact, requires only the discretization of the boundary of homogeneous regions and, consequently, is particularly suited for the analysis of problems having a small outer surface and a large volume, condition which is met by the majority of tunneling problems.[138–142]

An improvement of standard elements in view of the analysis of tunnels in unbounded media is represented by the so-called infinite elements, that have been formulated and applied in the framework of both finite element and boundary element methods.[143–145]

A parallel improvement of the boundary element technique consists in the use of 'coupled' approaches in which this method is adopted in conjunction with other types of elements or with different numerical techniques. For instance, boundary elements have been coupled with beam elements, for an efficient evaluation of the stresses within the liner[146] and with the methods of characteristics, for determining the boundary between elastic and plastic regions around tunnels.[147]

It can be observed, however, that the large majority of papers on coupled approaches deals with the coupling between boundary elements and 2D or 3D finite elements.[148–155] These contributions refer to 2D[151] and 3D[152] problems in which, in addition to the linear elastic behaviour of the medium, also non-linear[153,154] and time-dependent[155] material models are considered.

2.8. Back analysis and 'observational' design method

A link between the boundary element method and a different field of study can be seen in Reference 156 in which this method was adopted for the solution of backanalysis problems related to the excavation of tunnels.

Backanalysis techniques[157] have been introduced in geotechnical engineering for determining the 'average' mechanical parameters of soil/rock masses on the basis of field measurements performed during excavation or construction works, or for the evaluation of the rock pressure acting on linings or support structures on the basis of deformation measurements.[158]

These procedures can be seen as a practical tool to be adopted in the context of Karl Terzaghi's observational design method[159,160] and of its application to tunneling engineering according to Rabcewicz.[161]

Following the observational method, adequate measurements should be performed during construction/excavation works in order to monitor their progress and to show possible discrepancies between the conditions assumed in the design and those actually met in the field. If such a difference is observed, a backanalysis allows to refine the values of the mechanical parameters of the rock and to modify, if necessary, the design or the construction procedure.

The observational design strategy was considered in one of the early applications of numerical back analysis[162] in which the displacements measured during the excavation of a pilot tunnel were used to evaluate the rock pressure adopted in the design of the permanent support of the main tunnel.

The subsequent developments could be roughly subdivided into three main categories. The contributions belonging to the first two groups concern, respectively, the backanalysis of the loads acting on tunnel linings[163–165] and of the components of the *in situ* stress state prior to excavation.[166–168]

Most of the published studies, however, belong to the third group and deal with the evaluation of the mechanical parameters of the soil/rock mass surrounding the tunnel.[169–178] Different material models have been adopted in these studies, ranging from linear elastic[170], to elasto-plastic[177,178] to time-dependent[172] models.

Some of these studies[169,174] considered the simultaneous evaluation of the mechanical parameters and of the *in situ* stresses, while other studies adopted a probabilistic view point for this problem.[176]

3. CONCLUSIONS

This brief summary indicates that, starting from the early applications in the mid 1960s, the development of the numerical methods in tunneling engineering has been characterized by a steady growth and by an increasing interest of both academic and professional communities.

It is quite likely that additional progress on this subject will take place in the future and that new areas will emerge and will grow.

It seems reasonable to assume, for instance, that new numerical procedures for stress analysis will become popular, alternative to the well-established finite element and boundary integral equation methods. Among them, the so-called spectral collocation method[179,180] appears as a potentially successful candidate.

It is also possible that new numerical algorithms will be developed, substantially different from those customarily adopted for the interpretation of experimental data and field measurements. In fact, recent papers[181,182] suggest that the so-called neural network models, already applied in various fields of economy and science, could become a powerful tool also for the solution of engineering problems.

These considerations indicate that much work has still to be done in this field which represents one of the promising areas for research in geotechnical engineering.

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